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The Use of Digital Image Correlation in Explosive Experiments

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Abstract. Digital image correlation (DIC) was used as a diagnostic tool in two series of scaled, water-tamped explosive experiments. This paper presents the results from the two series that highlight DIC as a unique tool that provides a means of obtaining displacement measurements from which full-field strain, strain-rate and velocity measurements can be determined. The experiments described consisted of an explosive charge submerged in aquarium-like structures that had one side made from Aluminum 6061-T6. The aluminum sides of the aquariums were prepared so that they could be used in conjunction with a DIC system providing real-time, high-speed digital images from which subsequent plate deformations were derived.

The analysis of each experimental set produced a series of output data files that contained information regarding the plate displacement based on a reference image taken prior to detonation. The output displacement, strain data and the time between frames were used to determine plate velocity and strain-rate data. The output data was available in both 2D and 3D and was saved as picture files and video files. The displacement (with rigid body motion removed), strain and velocity were extracted from multiple locations over the plate surfaces and compared, one data set to another. The data was also compared to analytical models that were developed to predict plate response to the pressure pulse from the explosive charge.

Introduction

The diagnostic tools used in experiments provide the means for understanding the associated physical phenomena. Transient displacement measurements are, along with pressure and temperature, a key component in explosive-related experiments. Techniques that have become standard in the study of explosive events, such as photonic Doppler velocimetry (PDV), VISAR, Fabry Perot and the use of streak cameras, can provide high quality measurements of displacement.¹ These techniques, however, lack

the capability of providing full-field measurements of deformation. Full field displacement measurements provide the potential for measuring other important behavioral phenomena, such as, for example, strain concentrations or part rotations. Also, full-field measurements are particularly effective in model validation in that they show a more complete record of deformation compared to more traditional point-to-point measurements. The more exhaustive record that DIC provides assists the investigators in evaluating how certain boundary conditions are affecting the data.

Digital Image Correlation

Digital image correlation (DIC) is a non-contact, optical measurement technique that combines multi-frame camera imaging with computer processing and analysis to yield full-field displacement maps. These maps may be conveniently translated into a wide variety of surface strain data, including axial and shear strain maps as well as maps of absolute and relative displacements, rotations, curvature, velocity and strain rates.²

Using a single monochromatic digital camera, a DIC system may be used, with certain constraints, to analyze displacements and strains on flat surfaces. By using the stereovision achieved with a pair of synchronized cameras mounted at an offset and with a converging focus, the system may be used to analyze contoured, 3-dimensional, surfaces. DIC systems are highly flexible in that they may be used to analyze very large surfaces (e.g. aircraft structures), or very small surfaces like those observed using a scanning electron microscope. In addition, the process is equally applicable to the analysis of slowly changing phenomena like creep, as it is to rapidly changing phenomena like the explosively driven plates that will be discussed in this paper.

The development of high-speed and ultra-high speed cameras coupled with advances in computing power have made the use of DIC an attractive tool for experimenters in the energetic materials and blast mitigation communities.³⁻⁷

The deformation and motion of witness plates, the initiation of energetic material itself, the motion of missile bodies and, at lower speeds, the quasi-static mechanical properties measurements of plastic-bonded explosives (PBXs) have all been characterized using some form of DIC.^{8, 9} The work reported in this paper demonstrates the use of DIC to examine the motion and deformation of witness plates from two series of explosive experiments conducted to study the different effects of various underwater blast mitigation techniques.

Experimental Series

The results from six tests are presented in this paper. The six tests make up two series of

experiments conducted in 2009 at the Lawrence Livermore National Laboratory (LLNL) in the High Explosives Applications Facility (HEAF) in Livermore, California. The six tests are summarized in Table 1.

Table 1. Experimental series

Aquarium Type	Mitigation Technique	Speckle Style
Small	None	Paint
Small	Air-filled Plastic Tubes	Paint
Small	Mylar/Air	Paint
Small	Air	None
Large	None	Adhesive Film
Large	Air-filled Plastic Tubes	Adhesive Film

The small aquariums held approximately 11.4-liters of de-ionized water mixed with a surfactant and the large aquariums held about 265-liters. The relevant dimensions for the aquarium assemblies are given in the sub-sections below. The different mitigation techniques evaluated in this study include 1) no mitigation (only water existed between the explosive and the aluminum plate), 2) air-filled plastic tubes, 3) a Mylar sheet creating an air pocket between the explosive charge and the aluminum plate, and 4) air. In each case the explosive charge was arranged so that it was located along the vertical center of the aquarium at a location several centimeters from the aluminum plate.

The speckle pattern used in each test was either produced using Rust-Oleum® spray paint or produced with a combination of 3M Controltac™ adhesive film and black markers. The fourth small aquarium test did not use DIC to monitor deformation during the explosion and thus, did not require the plate preparation, but the post-test plate deformation was measured using DIC.

In running these tests there were several key factors that were fundamental to achieving good quality DIC results. These factors included precise synchronization of the images as well as durability of the target surface, especially as it related to the preservation of speckling during deformation. Each of these topics will be described for each series in their respective subsection.

Prior to describing the details of each individual series, a short note on the importance of lighting for DIC is provided.

Lighting

The amount of light needed in photography is related to the speed of image acquisition. For experiments involving explosively driven plates, the event of interest takes place in a few milliseconds and thus, the required frame rate is in the tens-of-thousands. Due to the short exposure time, images taken at high frame rates require a significant amount of light. For the experiments reported in this paper multiple 1000-Watt Altman 1000Q Follow Spotlights were used for illumination. These lights project a high intensity spot onto a target. The spot produced is not uniform in intensity and the size of the spot is a function of the proximity of the light source to the target. The distance from the light to the target was highly constrained in our tests because of the size and geometry of the shot tank that was used. Due to these factors multiple lights were needed to evenly light the target for DIC. In general, larger targets require more lights to develop a satisfactorily evenly lit target.

Small Aquarium Shot Series

The small aquariums were cube-like with 24-cm on a side, and made from 6.35-mm Lucite. The explosive charges were 6.3 grams of the explosive LX-14 (95% HMX and 5% Estane by weight). One side of the aquarium was replaced with a 3.2-mm thick 6061-T6 aluminum plate to allow measurement of the blast-driven deformations.

The first series of tests had the cameras arranged to view half of the area of the aluminum plate that was coincident with the aquarium portion of the assembly. This series assumed half-symmetry about the vertical axis centered on the plate. Viewing only half of the plate made it possible to use a higher frame-rate/resolution combination. Phantom cameras have a set group of frame rate vs. resolution options available for use and, as with other cameras, the higher the resolution, the lower the available frame rate. As these experiments were designed, the optimization of frame rate and resolution was evaluated,

keeping in mind that the speckle size needed to be created after the spatial resolution of the area of interest was determined.

The area of interest was approximately 13-cm wide by 25-cm tall. The frame rate chosen for the first series was approximately 41,000 frames per second (fps) and the corresponding best available resolution was 256 x 512 pixels. The shots were conducted in the Gun Tank located in the HEAF at LLNL. The explosive/aquarium assembly was located in the tank with the lights while the cameras were positioned outside of the tank, as shown in Fig. 1.

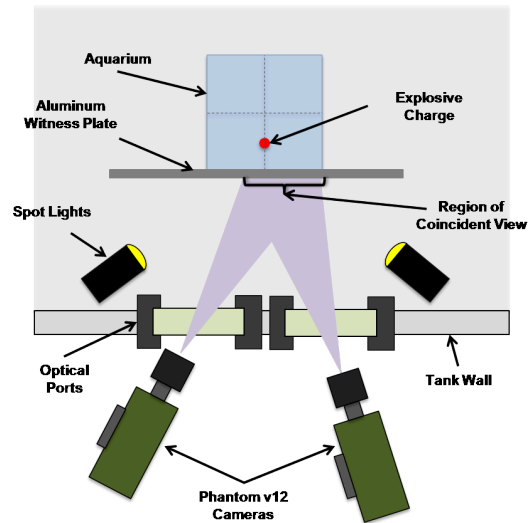


Fig. 1. Top view schematic of the cameras, aquarium assembly, firing tank and lighting used for the small aquarium shots. Note that the schematic is not shown to scale.

The aluminum plates used in the small aquarium series were treated with an allodyning process in an effort to increase the adhesion between the speckle pattern paint and the plate surface. Subsequent to the allodyning, the plates had a thin layer of flat white Rust-Oleum® paint applied to the surface of the plate that would be opposite to where the aquarium would be attached. After flat white paint was applied and allowed to dry a stencil was used to create the high contrast, random speckle pattern needed for DIC. The stencil was made by using an end mill to drill multiple 3-mm diameter holes through a thin sheet

of aluminum. After the holes were drilled, aluminum bar stock was attached to the edges of the thin plate in an effort to reinforce the stencil and to ensure that it maintained its flatness. The stencil was about 50-mm x 160-mm. Flat black Rust-Oleum® spray paint was then used as the speckle material. Due to the fact that the area of interest on the aluminum plate was larger than the stencil, the stencil had to be moved around the plate, with the paint being applied in various regions until the whole region of interest was covered. The process proved to be challenging in that the holes tended to clog with dry paint as the stencil was moved from one spot to another. Time was allowed in between regional applications so that the stencil would not smear the paint from previously applied regions. The finished products of the plate treatment and stenciling process are shown for the first two small aquarium assemblies in Fig. 2.

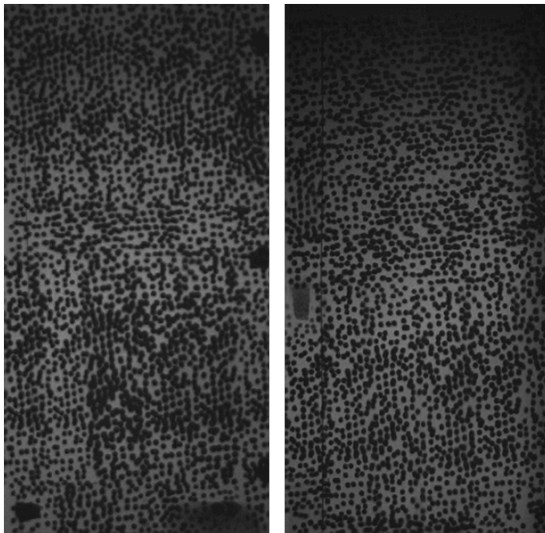


Fig. 2. Phantom camera images of the front view of the aluminum side of the first two small aquariums prior to the experiment. The speckle region is approximately 13-cm wide by 25-cm tall.

The Phantom cameras were synchronized using master-slave technique and then calibrated using a Correlated Solutions, Inc. calibration grid. The calibration was done to determine the intrinsic and extrinsic parameters of the cameras, which are necessary for the correlation algorithms used to

determine the displacement of the speckle pattern during the experiment.

Large Aquarium Shot Series

In the second series of experiments the full area of the plate that was aligned with the aquarium, an area approximately 72-cm wide and 55-cm tall, was imaged and the resolution was increased to 512 x 512 pixels. The increase in resolution resulted in a decreased frame rate, from ~41,000 fps to ~20,000 fps. The reduction in imaging speed was determined to be inconsequential based on the first series of tests.

The aquariums and the explosives used in the second series of tests were larger versions of the components used in the small aquarium series. The LX-14 charge used in the second series of tests weighed 146.5-g and the standoff from the aluminum plate was 17.53-cm. The aquarium walls were made from Lexan with a thickness of 0.95-cm and the thickness of the aluminum plate was increased from 3.2-mm up to 15.9-mm. While the portion of the aluminum plate that was adjacent to the aquarium was 72-cm by 55-cm, the whole aluminum plate was 122-cm by 122-cm. The extra plate material was needed to attach the plate to the vertical support structure, as can be seen in Fig. 3.

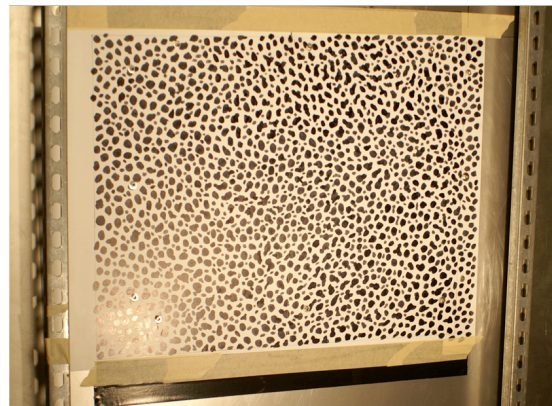


Fig. 3. Front view of the aluminum side of a large aquarium. The aluminum has a white adhesive-backed film (speckled with black ink) adhered to its surface. The speckle region is about 72-cm wide and the vertical support structure is visible.

The increased size of the aquarium assembly made it necessary to use a different blast chamber than was used in the first series. The 10-kg (explosive capacity) Spherical Tank located in the HEAF at LLNL was used for the second series. The same two Phantom v12 high-speed cameras were used but because of the different location, the spacing of the cameras and the lighting technique had to be modified. The optical ports on the Spherical Tank are located at 45-degrees intervals about the spherical center of the tank and are co-planar in the horizontal plane. The optical ports are made of quartz and are 38.1-mm thick. The spotlights were originally set-up to point directly at the aluminum witness plate but due to their intensity and the limited room for adjustment, the target could not be satisfactorily illuminated. As a correction to the problem a diffuser screen was brought in and hung from the top of the tank. The screen was positioned so that it did not obstruct the view of the cameras but so that it reflected the localized spots onto the large target surface. Fig. 4 shows a schematic of the tank and camera set-up and Fig. 5 is a photograph of the set-up showing the lights pointed at the screen.

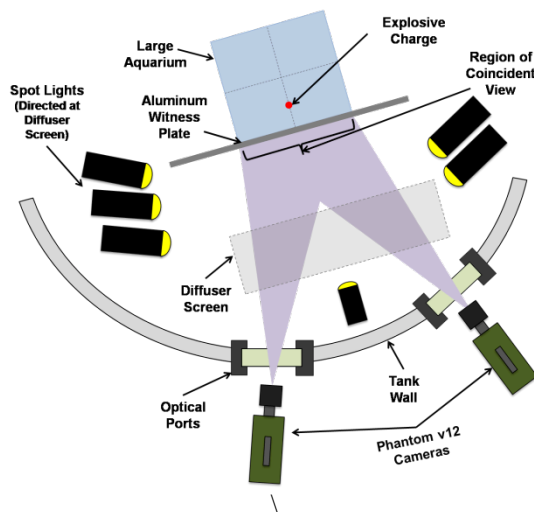


Fig. 4. Top view schematic of the cameras, assembly, firing tank wall and lighting used for the large aquarium shots. The schematic is not shown to scale.



Fig. 5. Photograph of the inside of the shot tank showing the spotlights directed at the diffuser screen with the light reflecting off it and towards the aquarium assembly (on left).

The air-filled plastic tubes used in the second large aquarium shot were 12.7-mm in diameter and were stacked in an array 15.9-mm thick.

The 3M Controltac™ was purchased in a size that would fit with a large printer available in HEAF. Unfortunately, the ink of the printer was not compatible with the Controltac™ material, which made hand drawn speckling necessary. In addition to the fact that the surface of the adhesive film was not compatible with the printer ink, the surface was somewhat reflective which caused strong glares from the intense spotlights. To help reduce the glare the Controltac™ was lightly hand-buffed with an adhesive cloth and then wiped clean. Black permanent markers were then used to apply random speckles to the film in a way that the speckles were at least three or more pixels wide when imaged. A finished example of the large aquarium speckle pattern is shown above in Fig. 3.

Results

The image correlation resulted in output data files that contained information regarding location and displacement. Using the relative displacement of the speckles on the target's surface computer algorithms determined the relative motion of the speckles in each image, compared to the speckles at time = 0 sec. Synchronized, high-speed videos were acquired from the pair of calibrated Phantom cameras for the first three small aquarium shots and the two large aquarium shots.

The Phantom v12 cameras were triggered on the capacitive discharge that was used to initiate the RPI detonator. Videos in the form of cinema (.cin) files were created from the camera and were then deconstructed using the Phantom camera software. The individual files were subsequently named in a way that was compatible with the DIC software and the two cameras' file sets were input into the DIC system as matched pairs.

Deformation Measurements

Using the calibration data calculated from images taken of the calibration grid, the sequential images of the deforming plate for each experiment were analyzed. The deformation results were output in files that contained the full-field displacement information for each location that stayed within the unobstructed coincident area of interest. Select data, including the out-of-plane (w) displacements, the strain, and the velocity from the experiments have been chosen for display in the next paragraphs.

Displacement measurements are shown in the form of lineout plots in Fig. 6 for the first three small aquarium shots. In addition to lineout data, the full-field displacement progression is shown in sequential color contour plots in Fig. 7 for the first small aquarium shot. Fig. 8 shows sequential color

displacement plots from the first large aquarium shot. The information contained in each output file from the DIC system makes it possible for the experimenter to examine the data as lineout, contour plots or as individual point data.

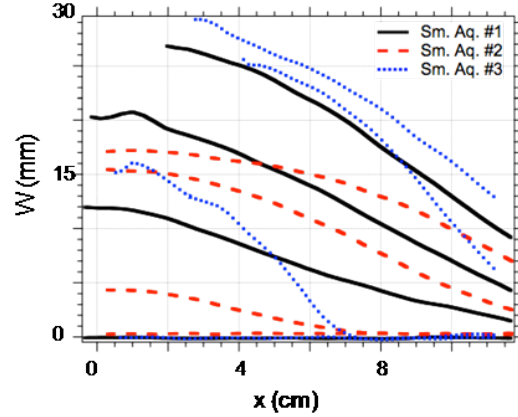


Fig. 6. Plot showing the w -displacement in mm as a function of location along the x -axis at the vertical centerline of the small aquarium plates. The plot shows a progression in time from 0-s to 0.1-msec, 0.3-msec and then 0.5-msec for each of the small aquarium plates that used DIC. The central area on the plot of Sm. Aq. #1 and #3 near the top center is the portion lost due to spall.

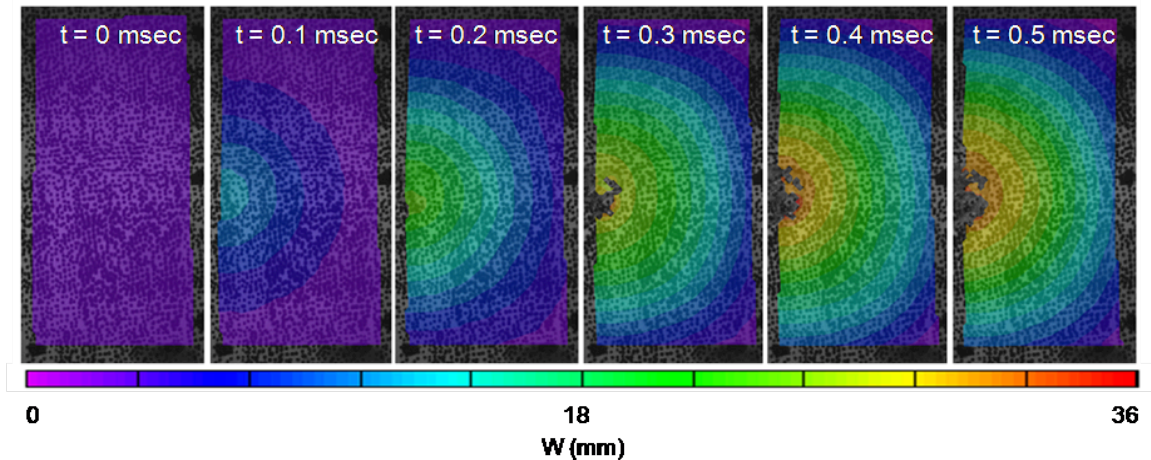


Fig. 7. A sequence of output displacement contour files from the first small aquarium shot showing the out-of-plane plate deformation at 0.1-msec intervals from 0 to 0.5-msec. The deformation shown above has the rigid body displacement removed. The small area of disruption in the color contour is the result of the speckle paint spalling off of the surface.

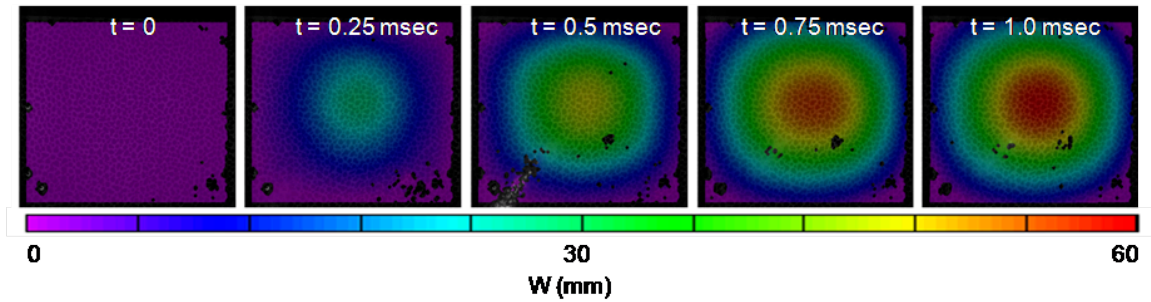


Fig. 8. A sequence of output data files from the first large aquarium shot showing the out-of-plane plate deformation at several points in time. The deformation shown above has the rigid body displacement removed. The small areas of disruption in the color contour are a result of some minor signal loss due to areas of glare.

Fig. 9 shows the comparison of the out-of-plane displacement (w) in mm as a function of location along the x -axis of the plate for the large aquariums at equivalent points in time. Both sets of curves start at $t=0$ and progress to 1-msec at 0.25-msec intervals. The plate from the Large Aquarium #1 shot is seen to peak out in displacement at about 60-mm at 0.75-msec while the Large Aquarium #2 plate has a peak displacement of about 45-mm at 1.0-msec.

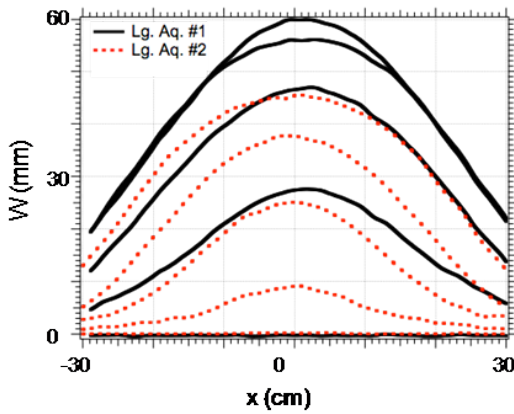


Fig. 9. Plot showing the w -displacement in mm as a function of location along the x -axis at the vertical centerline of the large aquarium plates. The plot shows a progression in time from 0-s to 1.0-msec at 0.25-msec intervals for each of the plates in the experiments.

The proximity of the 0.75-msec and the 1.0-msec traces for the first large aquarium shot

demonstrates the combination of elastic and plastic behavior evident in the deformation process.

Fig. 10 shows a comparison of the vertical strains computed along the same horizontal lineout used for the displacements shown in Fig. 9. The same progression in time from $t=0$ to $t=1.0$ -msec is shown. The strains from the Large Aq. #1 experiment peak at about 1.85%, whereas in the Large Aq. #2 experiment the strain peaks at about 1.0%.

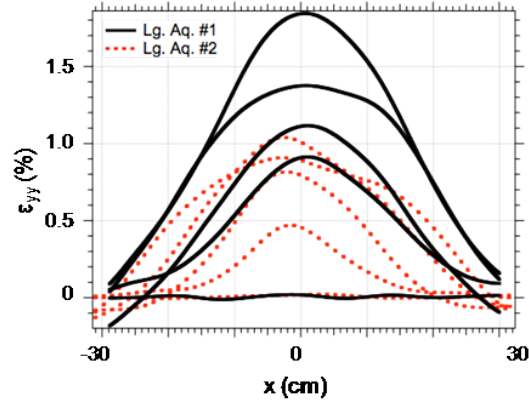


Fig. 10. Plot showing the strain as a function of location along the x -axis at the vertical centerline of the large aquarium plates. The plot shows a progression in time from 0 to 1.0-msec at 0.25-msec intervals for each of the two plates.

In addition to lineout data, individual points or data from small regions of the deforming surface can be averaged and then analyzed. An example of this capability is shown in Figures 11 and 12. Fig.

11 shows the velocity measurement of a point located at the approximate center of the two large aquarium plates. The data was extracted over 2-msec of the event and is plotted as velocity in m/s versus time in msec. There appears to be some aliasing taking place and may be due to the fact that the frame rate was not quite high enough to accurately capture the higher frequency velocity fluctuations. However, it can be seen that the center portion of the plate experienced a velocity of at least 130-m/s for the unmitigated shot (Lg. Aq. #1) and about 60-m/s for the air-filled tube mitigated shot (Lg. Aq. #2).

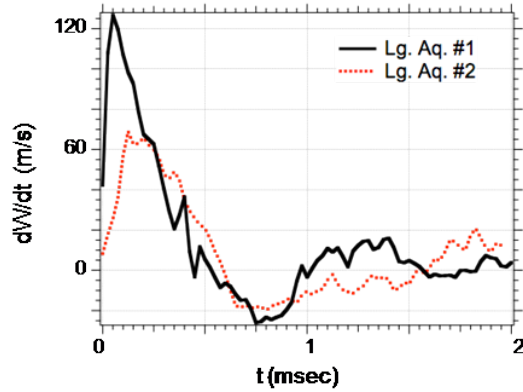


Fig. 11. Plot showing the out-of-plane velocity for the central region of the large aquarium plates.

The strains for a point in the central region of the plates were interrogated, and Fig. 12 shows the results. The plate from the Large Aq. #1 experiment is seen to have experienced a 1.85% strain at about 0.5-msec, while Large Aq. #2 peaks at ~1.0% slightly earlier.

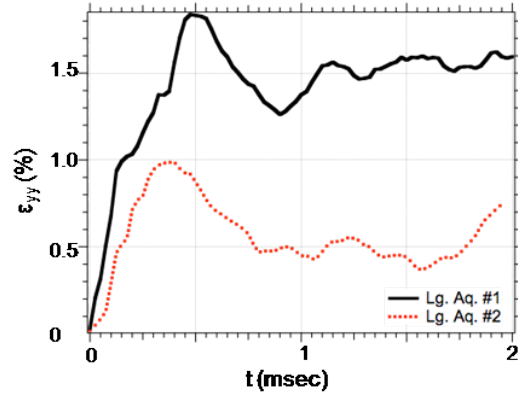


Fig. 12. Plot showing the strain versus time for a point in the central region of the large aquarium plates.

Post-Test Static Plate Measurements

In addition to the transient event data acquired during the deformation events, post-test static plate surface profile measurements were made using the DIC system. For plate-to-plate comparisons of mitigation types, as well as model validation of plastic deformation comparisons, post-test measurements were needed. To supplement the difficult task of hand measuring surface contours the DIC system was used as a tool to characterize the deformed plate shape. These measurements were accomplished by setting up the deformed plates and using an Epson Projector to project a speckle image from a laptop computer onto the diffuse plate surface. Once the DIC system was calibrated, the plates were imaged and the shapes were determined. Fig. 13 plots the contours of the four small aquariums.

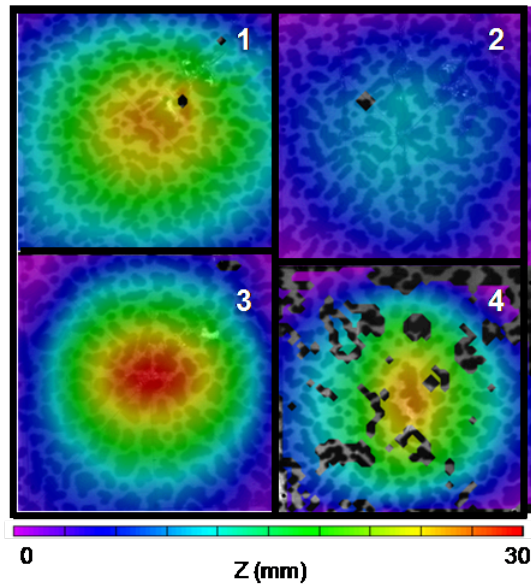


Fig. 13. Comparison of the permanent deformations experienced by the 4 small aquarium plates: 1) unmitigated, 2) air-filled plastic tubes, 3) Mylar/air pocket and 4) air pocket. In each case the minimum deformations are seen at the corners and are set to zero for these images. The greatest deformation appears in the center of plate #3, with a magnitude of 30-mm. Note that the color scales are equivalent for the four images. The gaps in the contour data in image four are due to regions of reflective glare.

The plates from the large aquarium shots were evaluated after the tests in the same way as the plates from the small aquarium shots. The results from the static measurements of the large plates are shown in Fig. 14. The region shown in the figure corresponds only with the region that was approximately adjacent to the area where the aquarium was in contact with the plate. The entire 1.22-m by 1.22-m plate is not shown, although we note that when the data from the entire plate is examined, interesting details relating to the effects of the boundary conditions emerge.

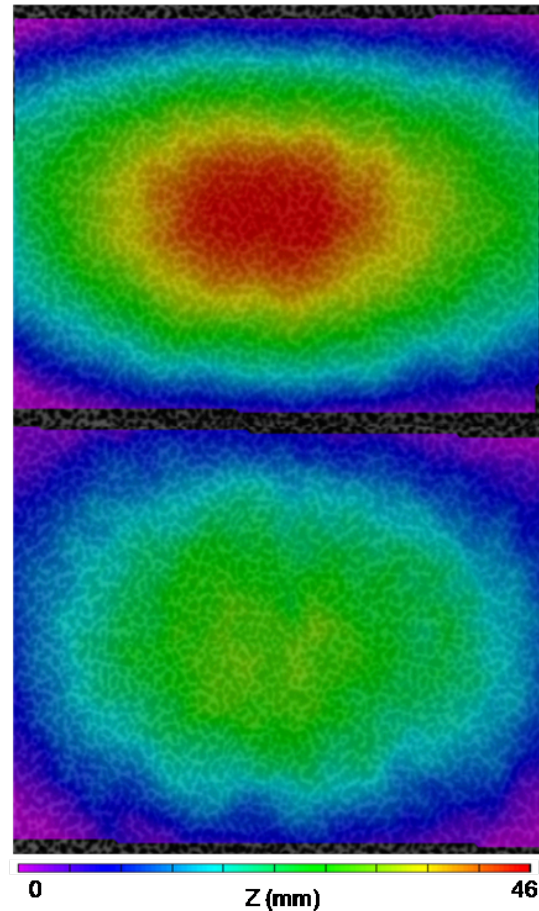


Fig. 14. Comparison of the permanent deformation experienced by unmitigated Large Aquarium #1 plate (top) with that experienced by the plate in the air-filled plastic tube mitigated blast in the second Large Aquarium shot (bottom). The metric in these images is the z-dimension in mm. The color scale is shown below the images. The range of the scale is 0 to 46-mm.

Discussion

The first test run was the water-tamped small aquarium shot. This assembly used the white spray paint background with black spray paint speckles stenciled onto the surface. The high-speed imaging showed that the location directly on the other side of the plate experienced paint delamination as the pressure wave traveled through the aluminum and reached the outer surface. While the data in the

immediate area where the spall occurred was lost, the overall displacement of the plate can be determined and was around 30-mm. The second test run was the air-filled tube assembly. The plate preparation was the same as the first test but this mitigation technique proved to reduce the blast enough so that no paint spalled off of the surface. The maximum displacement was also seen to have been dramatically reduced to a maximum of about 18-mm. The third test used a sheet of Mylar to create an air pocket between the explosive charge and the aluminum plate. Like the first test, there was evidence of significant spalling in the region that was in direct alignment with the explosive charge. Also, as with the first shot, while the data in the immediate vicinity of the spalled paint was lost, the overall behavior was clear. The maximum displacement of the third test was over 30-mm.

From the first three tests we learned that the air-filled tube technique provided the best mitigation. Also, we learned that we could use a lower frame rate to capture data. This then allowed us to use a larger region of view (512 x 512 rather than 256 x 512). We were then able to view the entire surface of the plate that was adjacent to the aquarium. This change proved to have a key benefit. The benefit was that the deformed image stayed in the area of coincident view longer, which allowed more deformation data to be acquired.

The large aquarium series produced results similar to the first series. The air-filled tube mitigation technique proved to dramatically reduce the blast effects as compared to the unmitigated (just water) version of the test. The out-of-plane displacements, the strain, and the velocity for the tube mitigation were all significantly lower. Additionally, the use of the adhesive-backed Controltac™ film may have contributed to the elimination of speckle spall. The results from the two large tests were clean except for some mild glare on the lower edge portions of the surfaces. This glare appeared as the plate moved rigidly towards the cameras.

The post-test contour measurements provided additional data that was useful to the modelers associated with these experiments.¹⁰

Summary

This paper reports the details regarding two series of explosive experiments in which DIC was used as a diagnostic tool in evaluating plate deformation as a function of the type of underwater blast mitigation used. Transient displacement, velocity, strain and static deformation were measured using multiple configurations of DIC hardware. The results showed that air-filled plastic tubing provided the best mitigation in both the small and large aquarium set-ups. Information related to the modeling efforts of these experiments can be found in work authored by Glascoe, *et al.*¹⁰

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